

Wind Turbine Blade Material in the United States: Quantities, Costs, and End-of-Life Options

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Abstract

Wind energy has experienced enormous growth in the past few decades; as a result, there are thousands of wind turbines around the world that will reach the end of their design lifetimes in the coming years. Much of the material in those turbines can be recycled using conventional processes, but the composite material that is the main component of the blades is more challenging to recycle. In the United States, turbine blades may be disposed of in landfills, adding a new solid waste stream to the material already being landfilled. This paper presents a spatially resolved estimate of the mass and volume of wind turbine blade waste in each state by 2050 and compares these amounts to estimates of the remaining landfill capacity by state. We estimate costs for each stage of the disposal process to indicate cost levels for alternatives. Assuming a 20-year turbine lifetime, the cumulative blade waste in 2050 is approximately 2.2 million tons. This value represents approximately 1% of remaining landfill capacity by volume, or 0.2% by mass. We also find that the current cost of disposing of blades in large segments or through grinding is relatively low in comparison to the overall life-cycle cost of energy. Based on these findings, landfill space constraints and disposal costs appear unlikely to motivate a change in waste handling strategies under current policy conditions. Instead, more profound shifts in recycling technologies, blade materials, or policy may be needed to move towards a circular economy for wind turbine blades.

Keywords

Wind turbines; blade material; end-of-life options; composite recycling

List of Acronyms

ATB	Annual Technology Baseline
CFRP	carbon-fiber-reinforced polymer
EOL	end of life
EPRI	Electric Power Research Institute
GFRP	glass-fiber-reinforced polymer
LMOP	Landfill Methane Outreach Program
NREL	National Renewable Energy Laboratory
USWTDB	United States Wind Turbine Database

1 Introduction

Wind energy is one of the world's fastest-growing sources of electricity generation, with significant global growth in installed wind energy capacity since the early 2000s. As these wind turbines reach the end of their design lifetimes, typically around 20 years, wind plant operators will need to manage end-of-life (EOL) materials that result from decommissioning. Some components, such as the tower and generator, can be recycled using mature commercial processes, but the composite materials in turbine blades are more challenging to recycle.

The annual rate of wind blade material being decommissioned globally, both on land and offshore, is projected to reach 2 million tons per year by 2050. Andersen et al. (2014) project that 400,000 tons of blades could be decommissioned annually by 2030, rising to 800,000 tons of blade material in 2050, based on a constant mass-to-capacity ratio of 10 metric tons per megawatt (t/MW). Liu and Barlow (2017) present a more detailed global estimate of blade waste that includes variation in blade mass with turbine capacity. They find a cumulative total of 43.4 million tons of blade waste globally by 2050, with 16% of the total (approximately 6.9 million tons) located in the United States. The flow of blade material being decommissioned tracks the initial sequence of installations, with early growth in Europe followed by the United States, China, and other regions. Based on this timeline, initial work to quantify and manage blade waste has mostly focused on the European context thus far; however, regional differences in policy and waste management practices make it valuable to consider blade waste management in the context of the United States.

Estimates of blade waste that are specific to the United States (EPRI 2018; 2020) indicate that the quantity of U.S. blade materials reaching EOL could be lower than the estimates presented by Liu and Barlow (2017). For example, using a constant mass-to-capacity ratio of 12.5 t/MW, the Electric Power Research Institute (EPRI) estimated cumulative U.S. blade waste at 1.2 million tons in 2040 and 2.1 million tons in 2050 (EPRI 2018). In 2020, EPRI presented additional blade waste scenarios, ranging from 50,000 to 300,000 tons per year by 2050 (EPRI 2020). The upper end of that range, which includes manufacturing scrap as well as EOL material, results in an estimated cumulative total of close to 4 million tons in 2050.

In the typical wind turbine life cycle, there are significant material and energy inputs during the manufacturing stage, which is the largest contributor to environmental impacts. The share of environmental impacts attributed to the manufacturing stage is close to 90% in some life cycle assessments (United Nations Environment Programme 2016). During the operation stage, there continue to be some material and energy inputs to maintain the turbine, but this stage is predominantly characterized by energy production. At EOL, material and energy can be recovered from some portions of the turbine; for example, by recycling steel towers. Material recovery reduces environmental impacts by offsetting a portion of the demand for virgin materials. Within a wind turbine, composite blades make up the largest fraction of material that is not recycled (Razdan 2019). If we consider a full wind plant, concrete foundations make up the largest fraction of material. Although the mass of foundations is larger than that of blades, there are factors that may reduce the quantity of concrete requiring disposal; for example, reusing existing foundations for new turbines or leaving the lower portion of a foundation in place when a wind plant site is decommissioned.

Wind turbine blades are primarily made of composite materials that combine high-tensile-strength fibers with polymer resins to form glass- or carbon-fiber-reinforced polymers (GFRP or CFRP). Composite materials are used for wind turbine blades because they are strong, lightweight, and durable, but their strength and durability present challenges for disposal. Between 80% and 90% of the blade mass is composite material, of which 60% to 70% is reinforcing fibers and the other 30% to 40% is resin (Jensen and Skelton 2018). Balsa wood or foam are used in the core of the blade, while gel coat and paint are used on the exterior (Beauson and Brøndsted 2016). Steel fasteners, copper or aluminum lightning protection, and adhesive are other common components within turbine blades. Separating these elements into homogeneous input streams for new uses is a key challenge for recycling EOL blades, with composite materials presenting the most difficulty. Some recycling processes do not attempt to separate composite materials, while processes that do separate composites may be unable to reproduce the structural characteristics of virgin materials.

A brief overview of EOL processes is included next, with energy demands and technology readiness levels of each process summarized in Table 1. The circularity strategy of each EOL process is categorized according to the framework described in Potting et al. (2017).

Landfill

Landfilling is the most common method for disposing of blades in the United States (Ramirez-Tejeda et al. 2017). The blades' large size poses a challenge for landfill operators seeking to utilize limited space efficiently. Because the blades are designed to withstand decades of strong winds and harsh weather conditions, they do not break down readily either by standard mechanical waste compaction or natural decay processes. Over time, organic materials in the blades will biodegrade, potentially releasing methane and other volatile organic compounds (Ramirez-Tejeda et al. 2017).

Incineration

Incinerating blades reduces the volume of waste and allows for energy recovery from the combustion of resin and wood. Glass fiber is incombustible, however, which reduces the calorific value of the composite material (Pickering 2006). Emissions from the combustion of epoxy resins may include harmful byproducts such as formaldehyde and carbon monoxide (Ramirez-Tejeda et al. 2017).

Cement coprocessing

Cement coprocessing has been carried out at commercial facilities in Germany in the past decade. It is suitable for GFRP but not CFRP blades. Incorporating GFRP into the production of cement allows for both material and energy recovery, although with a low economic value. First, glass fiber composites are burned in a cement kiln, where the energy recovered from the polymer resins displaces coal or natural gas typically used as fuel for incineration, reducing carbon dioxide emissions by up to 16% (EPRI 2020). Next, the residual glass fiber is incorporated into cement as "clinker," in combination with limestone and clay or shale.

Mechanical recycling

Composite material can be crushed or ground and incorporated into new composite products. The process may be carried out in multiple stages, with the initial stage possibly occurring at the

wind plant to reduce transportation costs. The resulting material ranges from fine powders to fragments with diameters up to 1 cm. However, the reduction in fiber length lowers the stiffness of the recycled composites below that required for turbine blades. As a result, the recycled material produced from mechanical recycling can only be used in products with less stringent design requirements, such as plastic lumber or sound-absorbing panels (Pickering 2006; Jensen and Skelton 2018; Mamanpush et al. 2018).

High-voltage fragmentation

High-voltage fragmentation uses electrical pulses to disintegrate solid material. Composite material is immersed in water between two electrodes that discharge repeated pulses of up to 200 kV, creating high-pressure shockwaves that break the composite into small fragments. The process is derived from rock mining techniques and has been applied to GFRP and CFRP at laboratory and pilot scales. Compared to mechanical recycling, high-voltage fragmentation produces longer and cleaner fibers, but requires higher-energy inputs (Mativenga et al., 2016).

Thermal recycling

High-temperature (400°–700°C) processing can separate glass or carbon fibers from the polymer matrix. Pyrolysis involves heating the composites in the absence of oxygen, producing combustible gas or liquid fuel from the polymers, and recovering the fibers in a useable form (Pickering 2006). After this process, the strength of glass fibers is reduced by close to 50%. In addition, although carbon fibers that undergo pyrolysis can retain almost all of their original material properties, they may have surface contamination that reduces their ability to bond to a new polymer matrix (Oliveux et al. 2015; Pickering 2006; Pimenta and Pinho 2011). Alternative methods of thermal recycling include fluidized bed gasification, which is better able to handle mixed and contaminated GFRP (Pickering 2006), and microwave-assisted pyrolysis, which heats more efficiently resulting in lower process energy requirements (Liu et al. 2019; Oliveux et al. 2015).

Chemical recycling (hydrolysis and solvolysis)

Chemical recycling methods involve the use of a solvent to break polymer bonds. They have been predominantly applied in laboratory settings rather than at industrial scale, and further variations (such as the use of supercritical fluids) are still being investigated (Andersen et al. 2014; Oliveux et al. 2015). If pathways for upscaling chemical recycling can be identified, they could potentially reduce environmental impacts from wind turbine blades by 14% to 44% compared to landfill (Liu et al. 2019).

Reuse and repurposing

If the lifetime of a complete turbine cannot be extended, the blades may be reused on other turbines as replacement parts. Blades can be refurbished and reused locally within a wind plant or resold on secondary markets (EPRI 2018). Alternative uses have been proposed for EOL blades, including public amenities such as playgrounds and benches (Beauson and Brøndsted 2016) or affordable housing (Bank et al. 2018).

Lifetime extension

One of the most effective ways to reduce the environmental impacts of currently installed wind turbine blades is to extend their lifetime. Using blades for more than 20 years improves their life-

cycle energy balance and reduces the need to manufacture new blades. Certification agencies have developed standards for turbine lifetime extension (DNV GL 2016; UL 2018) that prescribe methods for safety assessment. Older blades may require more maintenance, such as resurfacing or bolt replacement. Even with the incorporation of increased maintenance needs, extending blade life by 5 years is estimated to reduce life-cycle environmental impacts by 24%, while a 10-year lifetime extension reduces impacts by 48% (Liu et al. 2019).

Design for circularity

Changes in the design and material choices for wind turbine blades could lead to greater recyclability or potential for reuse. The choice of polymer in the composite material is one aspect of blade design that could lead to greater recyclability. The resins used in blades are typically thermoset resins that form strong cross-linked polymers during the curing process. A challenge for recycling thermoset composite materials is that it is difficult to break this cross-linkage to obtain raw materials for new composite products. In contrast, thermoplastic composites can be heated and remolded. Thermoplastic resins have been proposed as an alternative material for wind turbine blades that would facilitate recycling (Cousins et al., 2019).

Table 1. Comparison of EOL Processes

EOL Process	Circular Economy Strategy	Energy Requirement (MJ/kg) (Liu et al. 2019)	Technology Readiness Level (WindEurope 2020)
Landfill		0.3	9
Incineration	R9 – Recover	-4.2	9
Cement Coprocessing	R8 – Recycle	-4.2	9 (GFRP)
Mechanical Recycling	R8 – Recycle	0.3	9 (GFRP) 6/7 (CFRP)
Fluidized Bed	R8 – Recycle	22.2 (GFRP) 9.0 (CFRP)	5/6
Pyrolysis	R8 – Recycle	21.2	6/7 (GFRP) 9 (CFRP)
Microwave-Assisted Pyrolysis	R8 – Recycle	10.0	4/5
Chemical Recycling	R8 – Recycle	19.2	5/6
High-Voltage Fragmentation	R8 – Recycle	16.2	6
Life Extension 5 Years	R4 - Repair	1.4 (GFRP) 3.5 (CFRP)	9
Design for Circularity	R1 - Rethink	Varies by process	3/4

The problem of composite waste is not unique to the wind industry: fiber-reinforced polymers are increasingly used in other industries, including aviation, automotive, marine, and sports equipment. Wind turbines account for approximately 8% of the global composite market, as does aviation, while the market share for other forms of transportation is 26% (BloombergNEF 2020). As these products reach their EOL, the growing volume of waste improves the economic case for building dedicated composite recycling facilities. Development of viable recycling pathways for composite materials could also benefit the blade supply chain, as recycled carbon fiber could meet or exceed the strength of virgin fiberglass while lowering energy inputs and costs (Hagnell and Åkermo 2019).

In this paper, we provide a more resolved estimate of turbine blade material flows over time (up to 2050) and by state. In contrast to much of the other literature, we also quantify the impacts and costs of landfilling this material. The geographic resolution of our data allows for comparison of impacts between regions. We conclude by discussing our results in the larger context of sustainability and wind energy, focusing on the implications of our waste estimates for further research and development needs. More specifically, in Section 2, we describe our methodology for estimating the quantity of EOL blade material and remaining landfill capacity in each state, as well as the costs associated with each stage of blade disposal. We present the results and discuss their significance in Section 3, with conclusions and future research needs summarized in Section 4.

2 Methods

2.1 Blade material quantification

Wind turbine blades entering the waste stream over the next 20 years will come predominantly from turbines that are already in operation. The U.S. Wind Turbine Database (USWTDB) (Hoen et al. 2018) provides a comprehensive list of turbines operating throughout the country. As of April 2020, there were 63,794 turbines, ranging in capacity from 50 kW up to 6 MW, installed between 1981 and 2020. The database includes location, installation year, generating capacity, hub height, and rotor diameter. The current analysis excludes 1,087 turbines for which the installation year is unknown. Of the remaining turbines, between 4,000 and 5,000 lack other data such as capacity or rotor diameter; these parameters have been estimated by assuming they are equal to the average of all other turbines installed in the same year.

Projecting blade waste out to 2050 requires an estimation of future installations. For this analysis, we used the National Renewable Energy Laboratory (NREL) Standard Scenarios “mid-case” projections (Cole et al. 2019) of land-based and offshore wind capacity additions between 2020 and 2050. Projected capacities are subdivided by state, which allows for more detailed geographic analysis of blade retirements. To convert capacity additions into numbers of turbines, we linearly extrapolate the growth in turbine rated capacity from 2013 through 2035. This extrapolation leads to a projected average turbine capacity of 3.9 MW in 2030. Similarly, linear extrapolation of the rotor diameter results in a 167-m rotor in 2030. The extrapolated values are compared with the NREL Annual Technology Baseline (ATB) (NREL 2020) technology

assumptions for land-based wind¹ in 2030 in Figure 1. The projected average turbine capacity in 2030 aligns closely with the conservative ATB scenario, while the rotor diameter is closer to the moderate ATB scenario. Taken together, the values used in this analysis lead to a larger number of longer blades than would result from adopting the conservative or moderate ATB assumptions.

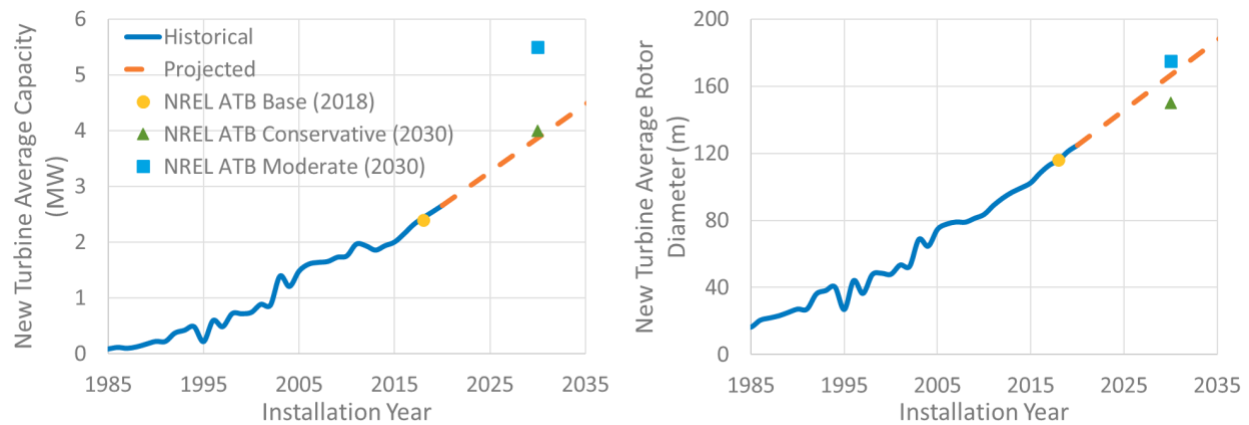


Figure 1. Historical and projected turbine capacity and rotor diameter

Note: Historical values are taken from the USWTDB (Hoen et al. 2018) and reflect turbines that are still in operation, which may not be representative of average turbines at the time of installation.

Throughout this study, we assume an average wind turbine blade lifetime of 20 years, which is a commonly used estimate of turbine lifetime (United Nations Environment Programme 2016). Because many turbines have not yet reached their EOL, there is uncertainty regarding the actual average lifetime. Economic analysis of repowering decisions indicates that 20–25 years may be appropriate for modern turbines (Lantz et al. 2013), while a manufacturer has suggested that future turbines may have a 40-year design lifetime (Knight 2019). On the other hand, blade lifetimes can be shortened by failure due to material and manufacturing defects or environmental causes such as lightning, or they may be replaced in a repowering process before 20 years of service. We examine the sensitivity of waste estimates to blade lifetime in Section 3.1.1.

Blade mass-to-capacity ratios reported by Liu and Barlow (2017) are used to convert present and future wind-generating capacities into material quantities. The mass of composite blade material per megawatt of installed capacity is calculated for each turbine based on its rated capacity as listed in Table 2. Liu and Barlow’s values for other sources of blade waste material are adopted as well: composite material waste from manufacturing is estimated at 17% of finished blade mass, blade replacements representing 3% of installed blade mass are assumed to occur in the sixth year of operations, and 5% of blades are assumed to be replaced due to repowering in the sixteenth year of operations.

¹ While our analysis includes both offshore and land-based wind, we consider representative land-based blade sizes because offshore turbines are projected to represent less than 10% of U.S. installed capacity through 2030.

Table 2. Blade mass in metric tons per megawatt of rated capacity, from Liu and Barlow (2017)

Turbine Rated Capacity (MW)	Total Blade Mass (kg/kW)
≤1	8.43
1–1.5	12.37
1.5–2	13.34
2–5	13.41
≥5	12.58

Due to blades’ hollow configuration, their volume may be more of a concern for landfills than their mass. We used rotor diameter data from the USWTDB to estimate the total volume of blade material currently installed in the United States, and the NREL Standard Scenarios “mid-case” with projected rotor diameters from Figure 1 to estimate future volumes. To generate this estimate, we assume that each turbine has three blades with lengths equal to half of the rotor diameter. Blade geometries for commercial turbines are typically proprietary, so the NREL 5-MW blade geometry (Jonkman et al. 2009) was analyzed to develop a relationship between the rotor diameter and the volume of each blade

$$V_{blade} = 0.0016 \times (D_{rotor}/2)^3$$

2.2 Landfill capacity

Landfill capacity in the United States was estimated based on data from the U.S. EPA Landfill Methane Outreach Program (LMOP) (U.S. EPA 2019). The database includes 2,629 landfills in U.S. states and territories, of which 1,268 were categorized as open in 2018. For this analysis, we only included open landfills in U.S. states that report design capacity, waste in place, and waste acceptance rates as of 2015 or later—a total of 855 landfills. The initial capacity estimate was calculated using the difference between the design capacity (in tons) and the tons of waste in place in 2018. Future landfill capacity was projected from the 2018 waste acceptance rate, which was assumed to remain constant on an annual basis until the landfill reached its design capacity, or until the projected year of closure in the LMOP database. Landfill capacity was aggregated by state, with a linear regression used to project the year in which statewide capacity would go to zero. The LMOP database reports capacity in tons; to estimate remaining landfill volume we used a typical density for compacted municipal solid waste of 1,009 kg/m³ (1,700 lbs/cubic yard) (U.S. EPA 2016).

2.3 EOL costs

In this section, we look at EOL costs for wind turbine blades. We focus on landfill costs as the baseline option, while indicating which costs would also be incurred for alternative EOL options and where the processes would diverge (Figure 2). For the initial decommissioning step, called teardown, we assume that a crane is used to remove the blades from the turbine. This cost can be deferred by lifetime extension but is required for all other EOL options. Teardown costs are estimated using NREL’s process-based balance of system cost analysis tool, LandBOSSE (Eberle et al. 2019), which was developed to model installation costs. The cost to tear down a

complete rotor is estimated at \$26/kW for a hub height of 80 m, with an adjustment of $\pm \$0.40/\text{kW}$ for each meter of hub height above or below 80 m (e.g., \$22/kW at a hub height of 70 m, \$30/kW at 90 m).

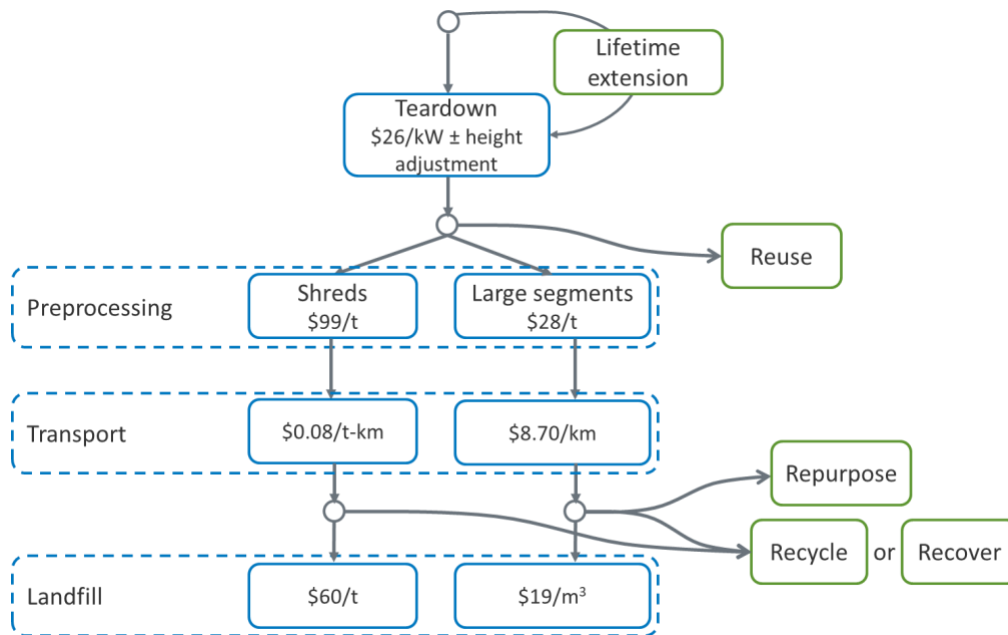


Figure 2. Blade EOL indicative costs and circularity pathways

After blades are removed from the turbine, some form of size reduction (preprocessing) is typically required to avoid the costs associated with transporting very large blades. We model two options for on-site preprocessing of the blades. One option is to cut the blades into segments of no more than 30 m in length, at a cost of \$25/ton [\$27.56/metric ton] (EPRI 2020). The other option is to coarsely grind the blades into pieces with a maximum dimension of 1–3 cm, for an estimated cost of \$90/ton [\$99.21/metric ton] (EPRI 2020). Large blade segments are assumed to be transported by semi-trailer, which can carry two segments at a time for an estimated cost of \$14/mile [\$8.70/km] (James and Goodrich 2013). A cost of \$0.12/ton-mile [\$0.08/metric ton-km] is used for shredded blade material transport (Langholtz et al. 2016). Similar preprocessing and transport costs would likely apply to recycling and repurposing as well as landfilling, although the distance from the wind plant site to the EOL facility would depend on the choice of EOL process.

Landfills in the United States charge a fee to accept waste that is typically called a “tip fee,” “tipping fee,” or “gate rate.” The national average landfill tip fee of \$55/U.S. ton (\$60.63/metric ton) is used for shredded blade material (Environmental Research & Education Foundation, 2019). Waste acceptance policies differ by landfill, but bulky items such as turbine blades may be charged tip fees by volume. In Texas, which has the largest quantity of turbine blades, the average volume-based tip fee in 2018 was \$15/cubic yard [\$19/m³] (Texas Commission on Environmental Quality 2019).

3 Results

3.1 Blade material

The current U.S. fleet of wind turbines includes more than 190,000 blades that will have been in service for at least 20 years by 2040. Based on a 20-year lifetime, a total of 235,000 blades will be decommissioned by 2050. The annual rate of retirements will be between 3,000 and 9,000 blades for the next 5 years, increasing to between 10,000 and 20,000 until 2040 (see FigureSI1 in Supplementary Information). Beyond 2040, the projected number of retiring blades decreases, but the average size of those blades will be larger than blades currently reaching their EOL.

The mass and volume of blades reaching their EOL annually in the United States are shown in Figure 3. The cumulative mass of EOL blades is projected to reach 1.5 million metric tons by 2040 and 2.2 million tons by 2050. The projected values agree closely with EPRI's estimate of 2.1 million tons by 2050 (EPRI 2018). Cumulative volume by 2050 is projected to comprise 63 million cubic meters of intact blades. Volume increases more steeply than blade mass in later years due to increases in blade length combined with design innovations to reduce weight.

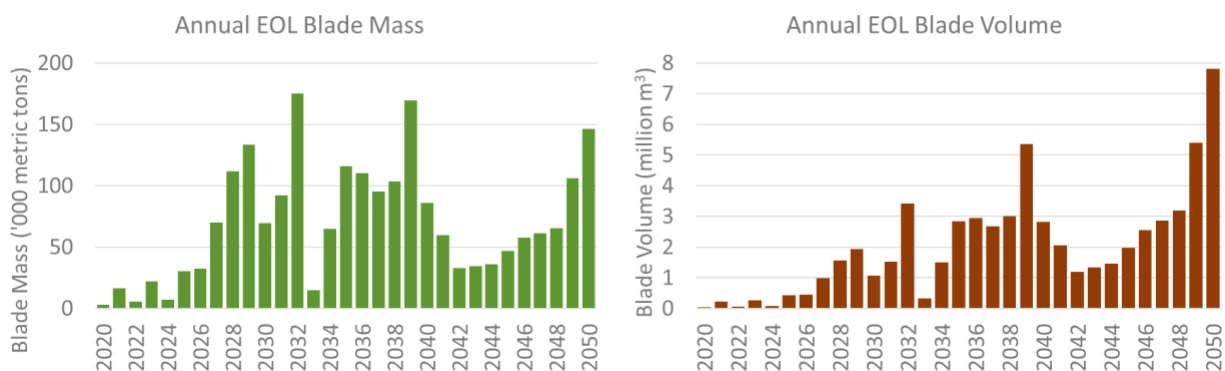


Figure 3. U.S. EOL blades to 2050

Note: A fixed 20-year lifetime was used to estimate EOL blade quantities

3.1.1 Parameter variation

The estimates of annual EOL blade material in Figure 3 are based on a constant blade lifetime of 20 years. While the assumption of a constant lifetime allows for straightforward and transparent calculations, it does not represent the range of lifetime durations that are actually observed in operational wind plants. The average blade lifetime may also differ from the assumed 20 years, so in this section we examine the sensitivity of the blade mass estimates to assumptions around blade lifetime.

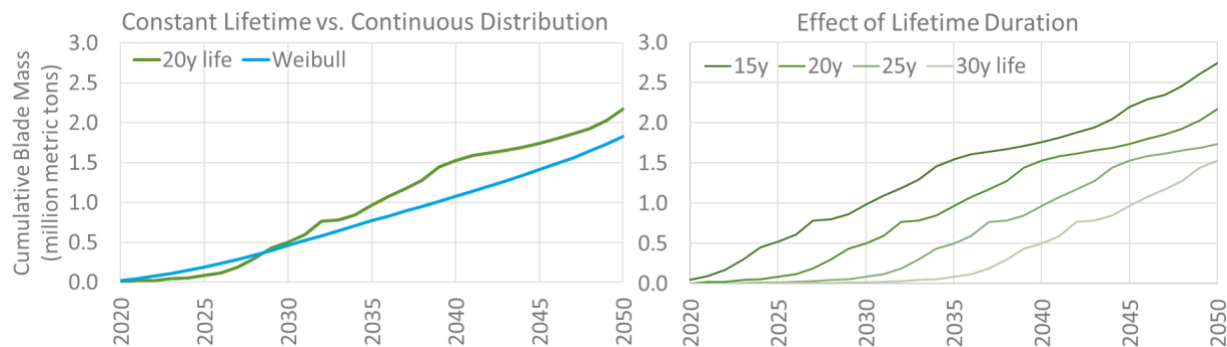


Figure 4. Sensitivity of cumulative EOL blade mass estimates to lifetime assumptions

Cumulative blade mass for a constant 20-year lifetime is compared with a Weibull distribution in Figure 4. The Weibull parameters are a characteristic lifetime $\eta = 20$ years and a shape factor $\beta = 2.2$ (Faulstich et al. 2016). Compared to a constant lifetime, the Weibull distribution predicts more blade waste between 2020 and 2028 due to early blade failures, but the total EOL blade mass is lower after 2030 because some blades are predicted to remain in service for longer than 20 years. The Weibull distribution also smooths the interannual variation that appears with the constant lifetime as a result of uneven growth in capacity additions. The righthand side of Figure 4 compares cumulative EOL blade masses for constant 15-, 20-, 25-, and 30-year lifetimes. The projected total mass by 2050 ranges from 1.53 to 2.75 million tons depending on the modeled lifetime. The effect of varying the lifetime duration is highly evident in the near term: compared to a 20-year lifetime, total waste in 2030 increases by 96% for a 15-year lifetime and decreases by 98% for a 30-year lifetime.

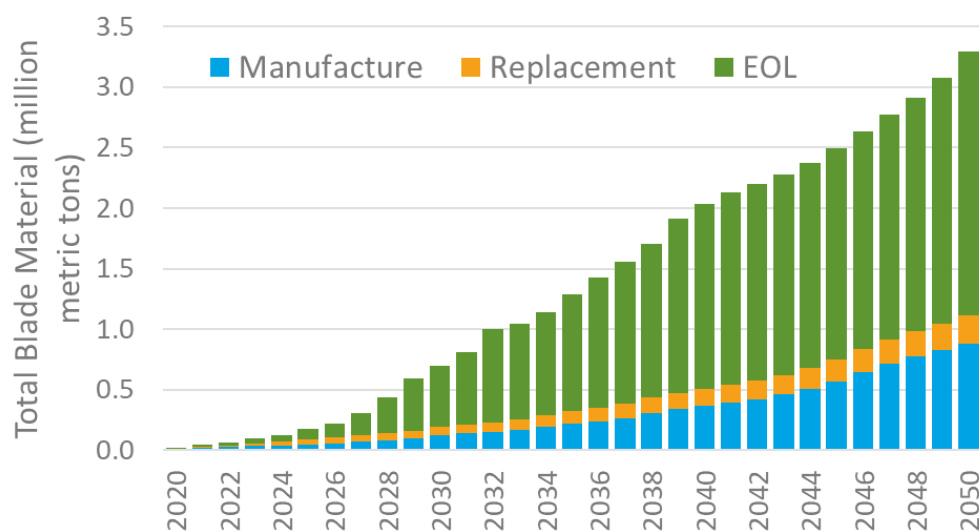


Figure 5. Cumulative blade material, including manufacturing and replacement

The mass of composite blade material entering the waste stream may also include material that is generated earlier in the life cycle. Figure 5 depicts the cumulative amounts of blade material projected to need disposal by 2050, based on EOL disposal after a 20-year lifetime, early replacements (due to failures or repowering), and manufacturing waste. Including these additional waste streams brings the cumulative total in 2050 to approximately 3.3 million tons.

The amount of manufacturing waste, which accounts for approximately 876,000 tons of composite material by 2050, may be affected by process innovation and the adoption of new materials over the next few decades, while the effects of new materials on EOL waste will become more significant 20 or more years later. Recycling or reuse of manufacturing wastes may also be simpler than EOL wastes because manufacturing scraps are more homogeneous and can be collected or processed directly at the production site, rather than being transported to a recycling facility from widely distributed wind plant sites.

3.1.2 Distribution by State

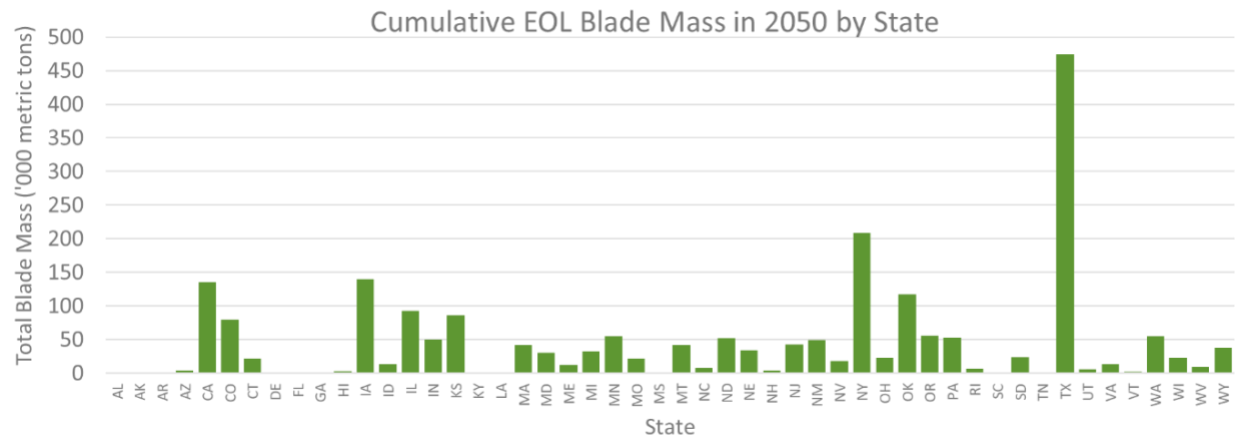


Figure 6. Cumulative EOL blade mass in 2050 by state

Figure 6 breaks down the cumulative EOL blade mass in 2050 by state, based on the location of installed turbines and projected capacity additions. Texas has the largest quantity of blade material, with approximately 474,000 tons by 2050. New York, Iowa, California, and Oklahoma are each projected to dispose of more than 100,000 tons of blade material. Corresponding volumes of EOL blade material in those states range from 2.7 million cubic meters in Oklahoma to 13 million cubic meters in Texas.

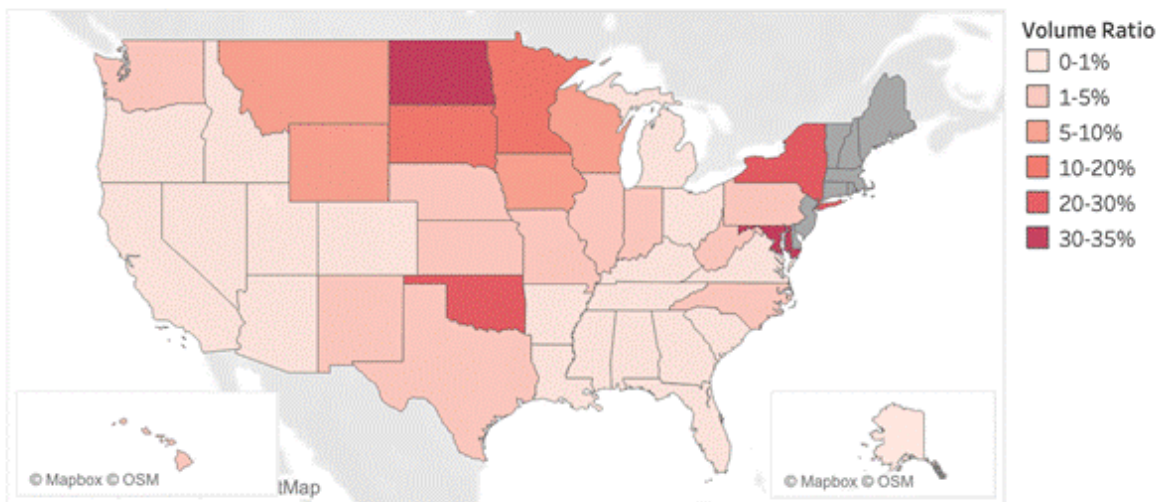
3.2 Blade material compared to landfill capacity

Using the methods outlined in Section 2.2, U.S. landfill capacity in 2018 is estimated at 12.7 billion metric tons, decreasing to 6.2 billion tons in 2050. Based on a density of 1,009 kg/m³, the remaining landfill volume in 2050 will be 6.2 billion cubic meters. Key assumptions affecting the landfill capacity estimates are that annual waste acceptance rates remain constant at 2018 levels, landfills can be filled to their design capacity before closure, and no new landfills will be constructed. The analysis also excludes landfills for which data reported by the U.S. EPA (2019) is incomplete. Several states, primarily in New England, are projected to fill their existing landfills by 2050—Connecticut already has no active landfills. If no new landfills are opened, waste generated in these states will need to be transported out of state, which already occurs in some places. This analysis does not attempt to model interstate waste transfer beyond what is already captured in the current waste acceptance data for operational landfills.

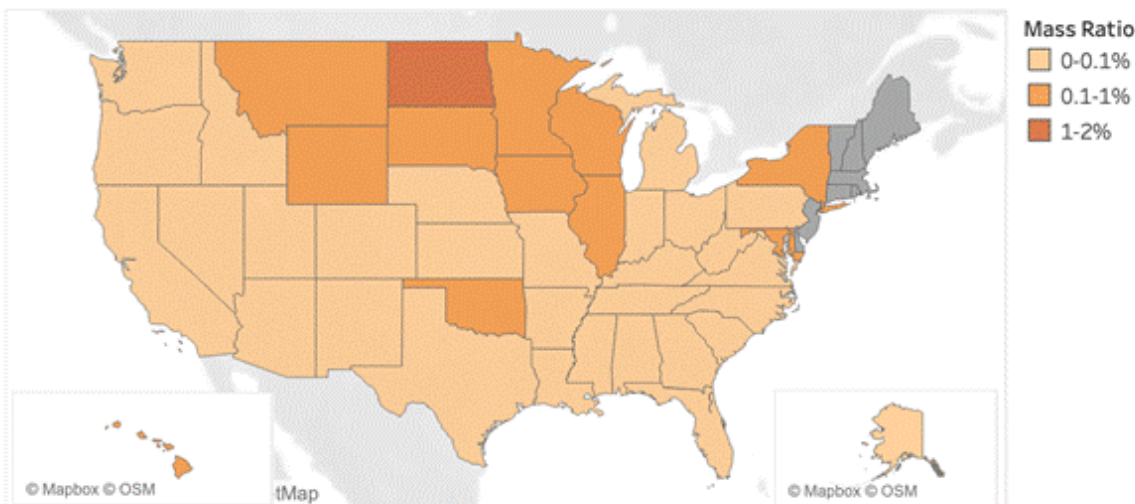
Considering the entire United States, the volume of EOL blade waste to 2050 represents approximately 1% of the estimated remaining landfill capacity in that year. The average density of intact blades, approximately 34 kg/m³, is much lower than typical solid waste in landfill. The

density of blade waste can be significantly altered by mechanical processing; for example, GFRP processed by a mobile shredding unit was found to have a density of 330 kg/m³ (Pickering 2006). By mass, the cumulative EOL blade material is equivalent to 0.02% of landfill capacity in 2050. Uneven geographic distribution of wind energy facilities leads to larger impacts in some states, as shown in Figure 7(a). The volume of EOL blades represents 30-31% of projected landfill capacity in Maryland and North Dakota, and approximately 20% in Oklahoma and New York. There is also a regional concentration of blade waste relative to landfill capacity in the northern Great Plains. Landfill capacity is limited in the Northeast even before EOL blade material is considered, which may incentivize regional development of alternatives to landfill. The proportion of EOL blade material with respect to landfill capacity in 2050 is smaller when evaluated in terms of mass rather than volume, shown in Figure 7(b). For example, blades could occupy up to 31% of the remaining landfill capacity by volume in North Dakota in 2050, while by mass, blades require less than 1.5% of projected capacity. (Blade EOL mass, volume, and landfill capacity are provided by state in TableSI1 in Supplemental Information.)

(a) Ratio of Blade Volume to Remaining Landfill Capacity in 2050*



(b) Ratio of Blade Mass to Remaining Landfill Capacity in 2050*



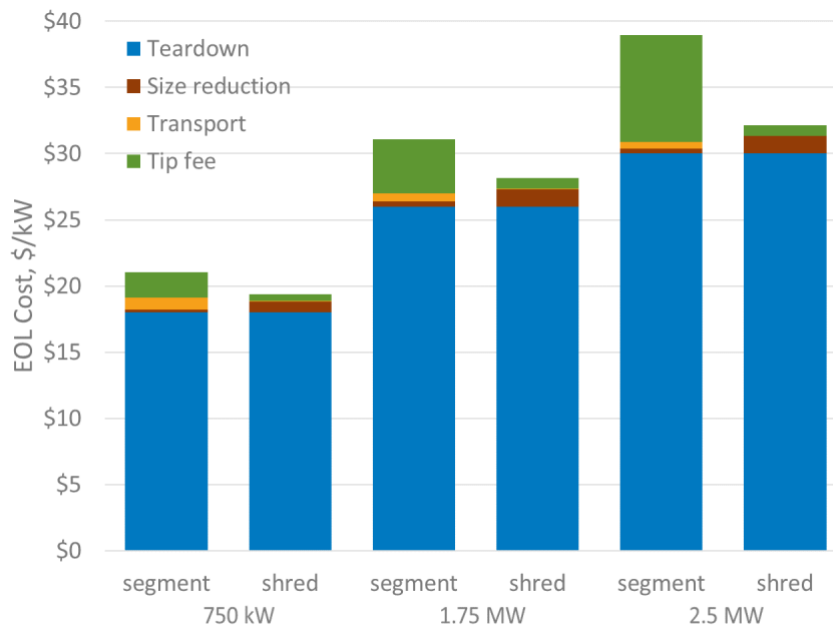
* States in grey are projected to have zero remaining landfill capacity in 2050, independent of blade material.

Figure 7. Volume (a) and mass (b) of EOL blade material in 2050 as a percentage of remaining landfill capacity in 2050 by state

3.3 Blade disposal cost analysis

Figure 8 compares EOL costs for three different turbine sizes based on typical turbine dimensions in 2000, 2010, and 2020. Costs are calculated under two different scenarios for each turbine: the blades are either cut into large segments for transport to landfill, where they are assessed a volume-based tip fee, or they are ground into shreds 1–3 cm in diameter at the wind plant, before being transported to landfill, where a weight-based tip fee is charged. The transport distance in both cases is 25 km. Although only two scenarios are presented here, other options—such as transporting the blades before shredding them or paying a weight-based tip fee for large blade segments—are also possible, depending on the available equipment and local landfill policies. The EOL cost per turbine ranges from nearly \$15,000 to \$100,000 for the three turbines

considered here. Adjusted for the generating capacity of each turbine, the range of EOL costs is between \$19 and \$39/kW. For comparison, the capital cost of a turbine—excluding installation and balance-of-system components—was approximately \$1,000/kW in 2018 (Stehly and Beiter 2020).



Representative installation year	2000	2010	2020
Rated capacity (MW)	0.75	1.75	2.50
Rotor diameter (m)	50	85	120
Hub height (m)	60	80	90

Figure 8. EOL cost variation with turbine size. Costs are compared for two processes: cutting blades into segments up to 30 m in length, or grinding to 1–3 cm shreds.

Teardown costs are the largest contributor to EOL costs, due to the need to mobilize a large crane to remove the rotor. Increasing turbine hub height leads to higher costs for larger turbines. Alternative teardown processes such as explosive demolition of the tower may provide opportunities for cost reduction. Grinding the blades on-site is costlier than cutting the blades into large segments but can lead to reductions in transport costs that become more significant as the distance to landfill increases beyond the 25 km modeled here. The main source of difference between the two processes is the tip fee, which is set by individual landfills and can vary within or between states.

Cost comparisons of other EOL options with landfilling should begin at the point of divergence between the two processes being compared, which may be preprocessing, transport distance, or the landfill tip fee versus recycling process costs net of the value of the recycled material.

4 Conclusions

As wind turbines reach the end of their design lifetimes over the next few decades, significant quantities of blade material will need to be managed. Based on current installations and future projections, we estimate the total amount of EOL blade material in the United States at approximately 2.2 million tons in 2050. The cumulative total is sensitive to assumptions regarding turbine lifetime, ranging from 2.75 to 1.53 million tons for lifetimes from 15 to 30 years, respectively. When compared to the remaining landfill capacity throughout the United States in 2050, this quantity of material could comprise 1% of landfill capacity by volume, or 0.02% by mass. Accordingly, we find that in the United States, constraints on landfill space alone appear unlikely to motivate a shift to a circular economy for composite wind turbine blades. Moreover, we find that the current cost of disposing of blades in large segments or through grinding are relatively low in comparison to the overall life-cycle cost of energy, suggesting that the status quo is likely to remain without alternative strategies to enhance sustainability, including changes in recycling technologies, blade design and materials, or waste management policies.

At present, several processes have been developed to recover material and energy from wind turbine blades, but they have not reached cost parity with landfiling. The largest contributor to EOL costs is the teardown process, which is common to all EOL options with the exception of lifetime extension. Costs for size reduction and transport are smaller and may be similar across EOL processes. Volume-based tip fees lead to significantly higher costs for blade disposal than weight-based fees. With a focus on wind turbines that have already been installed, lifetime extension provides an opportunity to significantly reduce the waste stream. Research that considers current manufacturing methods and materials while prioritizing opportunities for life extension may well be a meaningful way to enhance sustainability. Possible avenues for future work in this area include maintenance and repair strategies for older blades as well as diagnostic and inspection techniques that support certification of turbines to operate for an extended lifetime.

R&D investments to enhance the economic viability of alternative blade disposal strategies may also be worthwhile in areas where meaningful gains are plausible. Research into methods that increase process efficiency and lower energy consumption of alternative disposal and recycling methods may also be merited in order to reduce their cost and enhance parity with landfiling. Based on our brief review, we find that pyrolysis, chemical recycling, and high-voltage pulse fragmentation are worth further evaluation and study. Future work in this domain may evaluate other aspects of the wind energy waste stream, such as concrete waste from foundations.

Given the relatively low cost of current disposal strategies and the overall quantity of the waste stream relative to the larger waste industry, R&D strategies may also consider a more holistic design for circularity. Such concepts might reexamine blade design by considering new materials and production processes that foster recycling and reuse as well as new design possibilities that are not accessible to the traditional composites currently in use. Of course, such solutions will offer little to no benefit in terms of disposal for the existing fleet, but they may also offer the most sustainable route forward for the production of electricity from wind.

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Appendix A. Supplementary Information

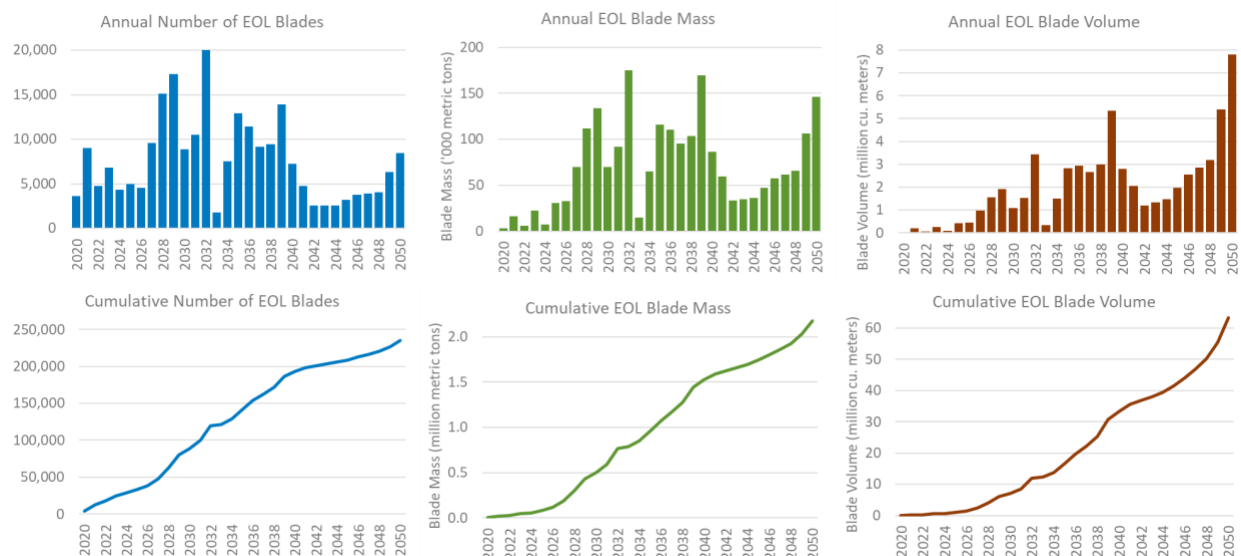


Figure SI1. Annual and cumulative amounts of EOL blade material based on a 20-year lifetime

Table SI1. Mass and volume of EOL blades and remaining landfill capacity by state in 2050

State	Mass of EOL blades by 2050 (metric tons)	Volume of EOL blades by 2050 (million m ³)	Remaining landfill capacity in 2050 (million metric tons)	Remaining landfill capacity in 2050 (million m ³)
AK	1,430	0.02	37	36
AL	–	–	162	161
AR	1	0.0002	53	53
AZ	3,581	0.06	400	397
CA	135,238	4.01	493	488
CO	79,260	2.33	236	234
CT	22,080	1.09	0	0
DE	29	0.0005	0	0
FL	25	0.0005	241	239
GA	4	–	185	184
HI	2,918	0.05	1	1
IA	139,939	3.20	40	39
ID	12,945	0.24	54	53
IL	92,408	2.15	81	81
IN	50,048	1.26	53	53
KS	85,614	2.01	157	155
KY	–	–	65	65

LA	–	–	100	99
MA	41,898	1.84	0	0
MD	29,923	1.22	4	4
ME	12,352	0.21	0	0
MI	32,558	0.87	114	113
MN	54,800	1.01	9	8
MO	21,772	0.58	44	44
MS	–	–	31	31
MT	41,234	1.60	19	19
NC	7,660	0.34	16	16
ND	51,894	1.12	4	4
NE	33,879	0.90	55	54
NH	3,782	0.08	0	0
NJ	43,025	2.02	0	0
NM	49,011	1.63	66	65
NV	17,714	0.81	985	977
NY	208,891	8.63	42	41
OH	22,414	0.64	259	256
OK	116,750	2.71	13	13
OR	56,113	1.15	409	405
PA	53,367	1.71	91	90
RI	6,382	0.24	0	0
SC	248	0.01	72	72
SD	24,066	0.59	5	5
TN	351	0.005	89	88
TX	474,288	12.93	625	620
UT	5,295	0.10	627	621
VA	12,988	0.59	120	119
VT	1,972	0.04	0	0
WA	54,517	1.35	125	124
WI	22,294	0.76	10	10
WV	9,924	0.18	13	13
WY	37,749	0.97	14	14